

# On the global and local magnetic fields in flare stars. Study of YZ CMi and OT Ser

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## ABSTRACT

Global magnetic fields of flare stars can evolve rapidly, in time scale of hundreds or dozens of days. We believe, that such changes result from rapid superposition of local magnetic fields generated by differential rotation of those stars. We discuss possible mechanisms of generation and dissipation of local and global magnetic fields in sample flare stars OT Ser and YZ CMi. Mechanism of magnetic braking of these stars is proposed here, in which differential rotation generates local magnetic fields, and eventually energy accumulated in local fields is radiated away by flares. We obtained estimates of the rotational energy and the energy of the global magnetic field of OT Ser and YZ CMi. It is shown that the energy of the local magnetic fields dissipated during superflare of YZ CMi on 9 February 2008 (UT 20:22:00) did not influence the global magnetic field of this star.

### Key words:

Stars: chemically peculiar – Stars: magnetic fields

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## 1. Introduction

Approximately 70 % of stars in our Galaxy are red dwarfs. Majority of stars in that group exhibit flare activity. Such a bright and intriguing form of light variations has drawn attention of many reserchers. Consequently, there are published many papers on that subject and thousands of red dwarfs were investigated up to now. For few objects the phenomena of flare light variations were observed in the full range of wavelengths, see Gershberg et al. (1999, 2011) and Katsova et al. (1999).

Our understanding of the nature of such light variations of red dwarfs was extended by the analogy to similar events observed on the Sun. Models comprehensively describing eruptions were presented by Hawley et al. (1995), Katsova et al. (1999), Katsova & Livshits (2001), Shibata & Yokoyama (1999; 2002), Stepanov et al. (2005) and others. However, there exist new observational data which cannot be explained by the existing models.

Flare stars show an incessant generation of local magnetic fields on the surface. In atmospheres of such objects energy of rotation and energy of convective motion of matter partly transforms into energy of the magnetic field. It is a reasonable assumption, that the power of such a magnetic field generator is constant at a given

evolutionary stage and can change only when a star change due to its evolution. The above prediction was frequently formulated by R.E. Gershberg. Average power of the generator is determined by the rotational velocity of a star, the measure of differential rotation, the effective temperature and mass of that star, Rossby number etc.

Other important measurable quantity is the total energy released during a flare. Accuracy of such a time-integrated measurement strongly depends on the time distribution of individual observations. Moreover, some flares remain undetected at all. Some flares occur at the rear side of a star. Some of them can be only partly visible to an observer and therefore can change their apparent properties due to the obscuration by a star.

At present there exist various techniques to account for and correct the above uncertainties, and we can infer the averaged power of the magnetic field generator. That quantity seems well estimated for the most observed M stars using, for instance, statistical investigations by Gershberg (1972), Moffett (1974), Lacy et al. (1976) and Kowalski et al. (2010).

Lacy et al. (1976) obtained the following relation for the best investigated flare stars

$$\log v = \alpha + \beta E_U, \quad (1)$$

where  $v$  denotes frequency of eruptions in  $\text{hours}^{-1}$ , variable  $E_U$  is the energy of eruption as seen in the U filter of the Johnson wideband UVB photometry. Note here, that the dominant fraction of flare energy is released in short wavelengths. Assuming estimated values of  $\alpha$  and  $\beta$  from Lacy et al. (1976) one can estimate in a rough approximation the lower limit for the averaged power of the generator of local magnetic fields for selected flaring stars. I.e. this is the estimate of energy emitted per 1 second as seen in the U filter.

Table 1: Estimates of the power of the local magnetic fields generator for selected flare stars.

Star	$\alpha$	$\beta$	$\log E_U$ (erg/s)
CN Leo	$28.6 \pm 3$	$-0.99 \pm 0.12$	$25.297 \pm 4.375$
UV Cet	$29.0 \pm 4$	$-0.98 \pm 0.14$	$25.963 \pm 5.624$
Wolf 424 AB	$24.1 \pm 5$	$-0.81 \pm 0.18$	$25.363 \pm 8.784$
YZ CMi	$21.4 \pm 2$	$-0.71 \pm 0.08$	$25.132 \pm 4.046$
EQ Peg A	$30.7 \pm 4$	$-1.00 \pm 0.14$	$27.144 \pm 5.626$
EV Lac	$20.7 \pm 3$	$-0.69 \pm 0.11$	$24.846 \pm 6.028$
AD Leo	$24.4 \pm 8$	$-0.82 \pm 0.27$	$25.419 \pm 14.375$
YY Gem	$12.6 \pm 3$	$-0.43 \pm 0.11$	$21.032 \pm 9.350$

## 2. Global magnetic fields in red dwarfs

Global and local magnetic fields in 11 red dwarfs were first studied in detail by Donati et al. (2008) and Morin et al. (2008; 2010). They showed, that red dwarfs exhibit two essentially different types of magnetic field structure:

1. SD (strong dipolar) – strong and stable two-polar magnetic field,
2. WM (weak multipolar) – weak multipole field.

The above two types of magnetic field configurations exist in various stars of the same masses and similar periods of rotation, see Morin et al. (2011a; 2011b).

Donati et al. (2008) and Morin et al. (2010) also discovered a puzzling peculiarity in magnetic behaviour of those stars: longitudinal magnetic field  $B_l$  of some objects (quantity integrated over the visible disc of a star) can rise or decrease steeply. We can demonstrate this amazing effect in case of flare star OT Ser using measurements by Donati et al. (2008).

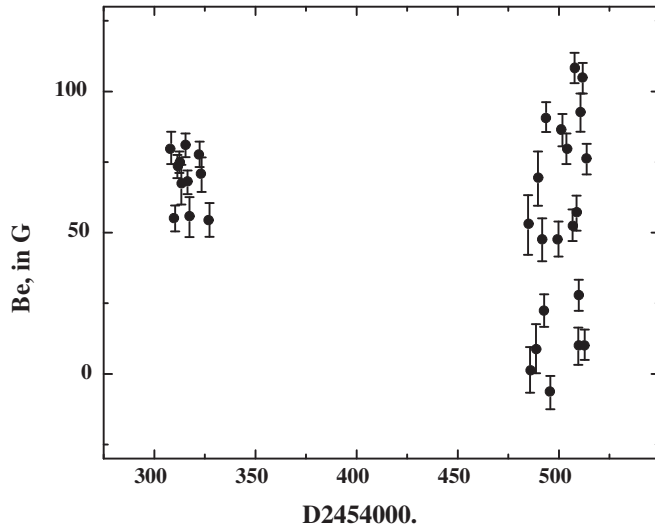


Figure 1: Flare star OT Ser. Magnetic field  $B_l$  as a function of  $HJD$ .

Fig. 1 shows run of discrete values of the longitudinal magnetic field  $B_l$  vs. time of observation in  $HJD$ . One can see that OT Ser was accidentally observed in two different states. In the first state the longitudinal component of the magnetic field  $B_l$  integrated over stellar disk shows low periodic variability of complex

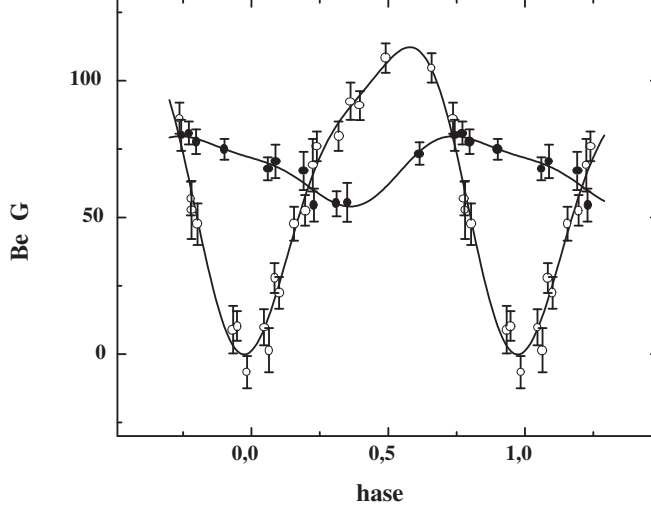


Figure 2: Magnetic phase curve  $B_l$  plotted against rotational phase for flare star OT Ser with the rotational period  $3^d.424$ . First and second set of observations (filled circles and open circles, respectively) are separated by about 180 days.

shape with amplitude 12 G about the average value 68 G. In the second set of measurements, which was obtained a half of the year later, that picture dramatically changed. Values of  $B_l$  rose significantly stepwise and now they show periodic variations with the period of rotation equal 3.424 days and the amplitude 54 G (4.5 times higher).

The most optimistic theoretical estimates predict the rate of evolution of the complex global magnetic field structure (like that observed in flare stars) of the order  $10^6 - 10^7$  years [22]. Therefore, changes of amplitude and shape of the magnetic phase curve within six months are spasmodic and such rapid changes indicate that in flare stars there exists fundamentally different mechanism of generation and evolution of the global magnetic fields than in stars on the upper part of the main star sequence.

Magnetic phase curve for OT Ser in the second state can be approximated by a double sine wave

$$B_e(\phi) = B_0 + B_1 \cos(\phi + z_1) + B_2 \cos(2\phi + z_2), \quad (2)$$

where

$$\phi = 2\pi \left( \frac{t_i - T_0}{P} \right). \quad (3)$$

with parameters  $B_0 = 64$  G,  $B_1 = 53$  G and  $B_2 = 13$  G.

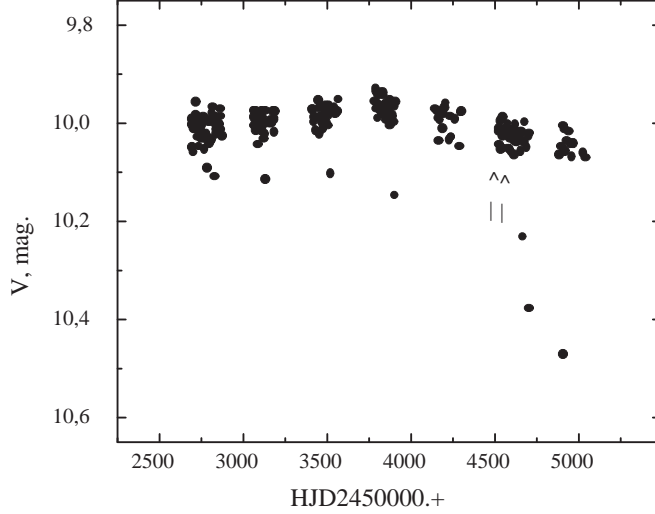


Figure 3: Light variations in V color of flare star OT Ser in years 2003–2010 determined by the photometric survey ASAS3. Average times for both  $B_I$  sets of the magnetic measurements are indicated by vertical arrows.

Therefore, OT Ser has changed the type of its magnetism from WM type (weak multipolar) to SD type (strong dipolar) during six months which separate both series of observations. It is of great importance to understand what happened to OT Ser in the time period between both states and what is the reason of such a qualitative change of its observable magnetic behaviour.

Fig. 3 shows variation of the apparent brightness of OT Ser in V color in years 2003–2010. Points V were taken from the database of the robotic photometric survey ASAS3 (Pojmański 1997). OT Ser shows a smooth long-term variability of brightness in that color without any distinct features in the light curve. Average times of both  $B_I$  sets of the magnetic measurements of OT Ser (as in Fig. 1) are indicated here by arrows.

### 3. Local and global magnetic fields: case of YZ CMi

Magnetic type of red dwarf YZ CMi points to SD star (strong dipolar). Morin et al. (2008) published measurements of this star obtained in years 2007–2008. Fig. 4 and Table 2 show, that the amplitude of magnetic variations of this star slightly decreased at that time period.

Fig. 6 presents magnetic phase curves for YZ CMi obtained in those years. As is easily seen, in 2007 the phase curve was approximated by a simple harmonic

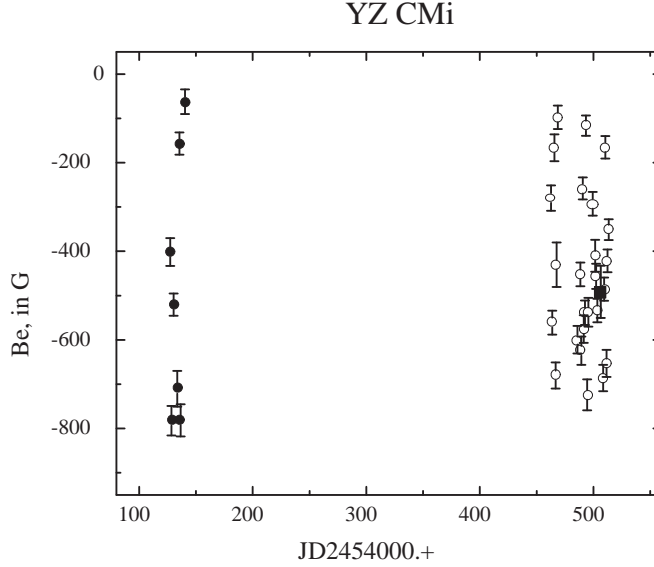


Figure 4: Measurements of the longitudinal magnetic field of YZ CMi in years 2007-2008 published in Morin et al. (2008). The second set of magnetic measurements (open circles) presents a single  $B_l$  point (filled square) obtained just after the end of superflare on 9 February 2008 UT 23:06:31.

wave with the parameters  $B_0 = -422 \pm 14$  G,  $B_1 = 300 \pm 16$  G and the period  $P = 2.7773$  days. Unfortunately, the total number of  $B_e$  points obtained in 2007 was not high. Phase curve obtained in 2008 shows more complex double wave structure with lower amplitudes. New parameters were given by  $B_0 = -446 \pm 6$  G,  $B_1 = 247 \pm 9$  G and  $B_2 = 106 \pm 9$  G.

Methods for obtaining the above phase curves are the same as in the catalog of the average magnetic phase curves (Bychkov et al. 2005).

On 9 February 2008 UT 20:22:00 a very strong burst started on YZ CMi. The superflare lasted for about 1 hour and was observed with the high-speed UBVR photometer and the 2-m telescope at the Terskol peak observing station (Zhilyaev et al. 2011). Then, authors estimated parameters of the flare, and the size and other parameters of the area on the star where that eruption occurred.

That event was among the most powerful eruptions ever observed in YZ CMi, taking into account the energy yield. At the peak of the flare luminosity of the star in U filter increased 180 times ! Then, the power received in U filter reached 20% of the bolometric luminosity of the star ( $M_{\text{bol}} = 10.25$ , Reid & Hawley 2005).

Fig. 5 presents estimates of YZ CMi brightness in the U filter during the superflare. End of flash has not been observed and it was necessary to extrapolate

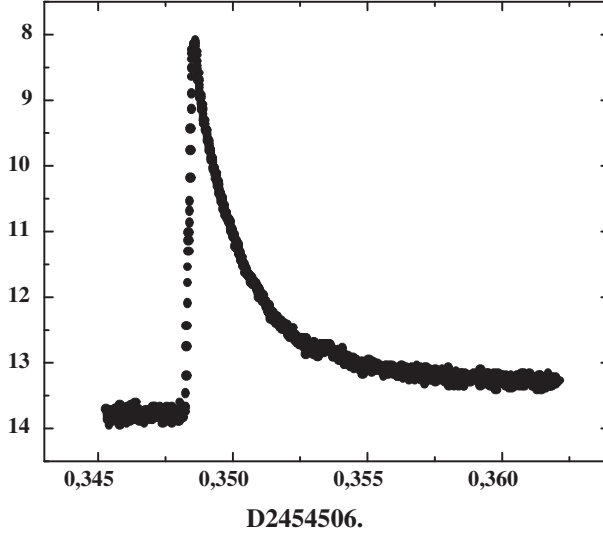


Figure 5: Apparent brightness of YZ CMi in filter U as a function of HJD during superflare on February 9, 2008 UT 20:22:00.

brightness variations in U filter to estimate brightness in the quiescent state. But it could not significantly affect accuracy of the total yield estimate of the flare and the time length of this eruption.

Accidentally, at the end of that superflare on 9 Feb 2008 UT 23:06:31, Morin et al. (2008) measured longitudinal magnetic field  $B_l$  of YZ CMi using the 2-m Telescope Bernard Lyot (TBL, southern France) equipped with NARVAL spectropolarimeter. This single estimate was obtained in the second set of  $B_l$  measurements for YZ CMi. In Fig. 4 this estimate is represented by a filled square. As can be seen in Fig. 4, even such a powerful eruption, or dissolution of the local magnetic field did not influence the global field structure of the star.

All estimates  $B_l$  from the second set of measurements (year 2008) are well described by the magnetic phase curve defined by Eq. (2) with parameters -  $B_0$ ,  $B_1$  and  $B_2$  quoted above. In order to show goodness of this curve (solid line in Fig. 6) we computed corresponding deviations of  $B_l$  points from the smooth phase curve.

Fig. 6 presents deviations of the discrete longitudinal field values  $B_l$  from the averaged phase curve. Position of the  $B_l$  measurement obtained on 9 Feb 2008 was indicated by a solid square, same as in Fig. 4. It is evident, that the  $B_e$  point does not distinguish from other measurements and the apparent trends in run of other  $B_l$  points represent just random inaccuracies in fitting by a double wave phase curve.

Fig. 7 shows those deviations from the magnetic phase curve (solid line).

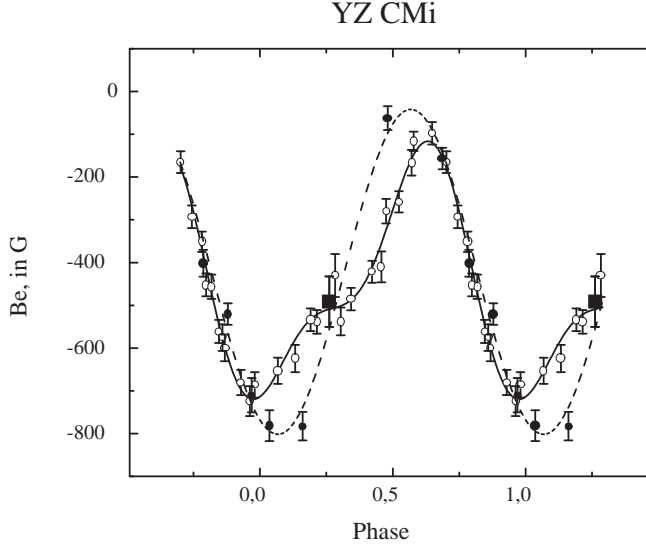


Figure 6: Magnetic phase curves for flare star YZ CMi with the rotational period  $2^d.7773$ . All  $B_l$  measurements were taken from Morin et al. (2008). Filled circles and dashed line present data of 2007 year and define a simple sine wave phase curve. Measurements obtained in year 2008 (open circles) define more complex double wave phase curve. Filled square indicates a single  $B_e$  observation obtained just after the end of the superflare on 9 February 2008, UT 23:06:31.

Again, the single  $B_l$  point measured immediately on the end of superflare (9 February 2008) is annotated by a large filled square. Fig. 7 clearly shows that this single  $B_l$  measurement is an average point and all deviations are random. We conclude that even such a powerful local magnetic field dissipation event had no effect on the global magnetic field.

Other authors also observed megabursts in this frequently observed flare star. For example, on 16 January 2009 UT max 04:32:00 at the peak flux of the flare luminosity of YZ CMi in U filter increased by 5.8 magnitudes (i.e.  $\sim 330$  times !), see Kowalski et al. (2010). Parameters of superflares differ from average flares not only by the amount of energy. Superflares also are events of significantly longer duration (Kowalski et al. 2010).

#### 4. Discussion of results

We can present approximate estimate of energy yield during the superflare of 9 Feb 2008 (Zhilyaev et al. 2011). Following Gershberg (1972), one should integrate the light curve over the time. That time equals approx.  $1.41 \times 10^4$  sec, i.e. it is the



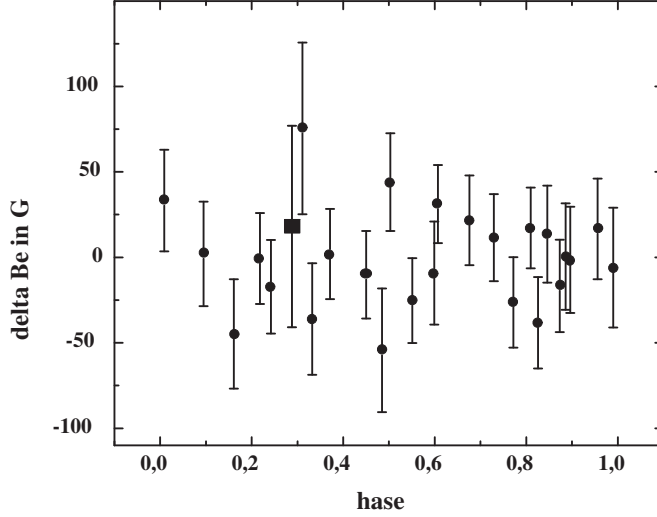


Figure 7: Deviations of  $B_e$  points from the phase curve for flare star YZ CMi with the rotational period 2.7773 days. The single  $B_e$  point annotated by a solid square was observed just after the superflare has ended on 9 Feb 2008 UT 23:06:31.

time period when YZ CMi radiated away that amount of energy in quiescent state. According to Moffett (1974) the average flux in U filter from YZ CMi in quiescence equals  $4.00 \times 10^{28}$  erg/s. Consequently, the integrated additional energy released at the time of the flare equals  $5.64 \times 10^{32}$  erg/s. Time necessary to accumulate such amount of energy equals ca. 1.3 years, if we accepted the average power of the local field generator with parameters quoted in Table 1. Such an estimate obviously contradicts observations.

If we accept the upper limit for an estimate for the power of the generator,  $\log E_U \approx 29.2$  erg/s, then the time period decreases to ca. 1 hour which is much closer to observational data. On the other hand, the observed power of the generator was significantly overestimated here.

We present below sample estimates of the mechanical energy of a star the energy of its global magnetic field. Energy of the rotational motion of a solid body equals

$$W_r = \frac{I\omega^2}{2}, \quad (4)$$

where  $I = kMR^2$  is the moment of inertia, coefficient  $k$  was determined by the mass distribution inside a star, and  $\omega = 2\pi/P$  stands for angular velocity of rotation. Exact value of the coefficient  $k$  was computed for a Lane-Emden model of a star in hydrostatic equilibrium, for politrope index  $n = 3/2$  corresponding to a convective

star.

Energies of the global magnetic fields of OT Ser and YZ CMi are estimated under assumption, that the field configuration in both stars is close to a simple dipole. This assumption follows the observational fact, that both magnetic phase curves are close to simple sine waves. Then, in a rough approximation the energy of magnetic field was estimated by

$$W_m \approx \frac{B^2}{8\pi} \times \frac{4\pi R^3}{3} \text{ erg}, \quad (5)$$

additionally assuming that the field is homogeneous in the volume of a star.

Estimates of the principal parameters in Table 2, as angles  $\beta$ ,  $i$  and the polar intensity of the magnetic field  $B_p$  were obtained following the Stibbs-Preston formalism (Stibbs 1950; Preston 1971).

Table 2: Principal parameters of flare stars OT Ser and YZ CMi.

parameter	OT Ser	2007	2008	YZ CMi	2007	2008
$M/M_\odot$	0.55			0.31		
Sp.type	M1.5 V			M4.5 V		
$R/R_\odot$	0.49			0.29		
$k$	0.00519			0.00191		
$P_{\text{rot}}$ in d	3.424			2.77729		
$V \sin i$ in km/s	$6 \pm 1$			$5 \pm 1$		
$i$ in degr.	$56 \pm 20$			$71 \pm 20$		
$B_0$ in G		$68 \pm 2$	$65 \pm 2$		$-422 \pm 14$	$-453 \pm 6$
$B_1$ in G		$12 \pm 2$	$54 \pm 3$		$380 \pm 16$	$250 \pm 9$
$\beta$		7	29	12		
$B_p$ in G		406	436		4498	4696
$W_r$ (erg)	$1.5 \times 10^{42}$			$1.6 \times 10^{41}$		
$W_m$ (erg)		$6.9 \times 10^{36}$	$1.3 \times 10^{36}$		$2.8 \times 10^{37}$	$3.0 \times 10^{37}$
$W_m/W_r$		$4.6 \times 10^{-6}$	$0.87 \times 10^{-6}$		$1.75 \times 10^{-4}$	$1.88 \times 10^{-4}$

Unfortunately, OT Ser was not previously included into the table of most frequently observed flare stars and, therefore, we could not collect enough data to estimate the power of the local magnetic field generator in this star (see Table 1). The only solution of this problem in OT Ser is to apply here that power for YY Gem, since both flare stars show most similar parameters.

If one assumes, that the global magnetic field of OT Ser was cumulated from the generator of local magnetic fields in the time period  $\approx 100$  days, then its power should be higher than  $1.5 \times 10^{29}$  erg/s.

## 5. Conclusions

Estimates collected in Table 2 show, that the rotational energy of a star is much higher than energy of its global magnetic field and certainly can be a source of 'fuel' for the dynamo mechanism for the magnetic field generation. In late-type dwarfs with differential rotation exists an efficient dynamo-like mechanism generating local magnetic fields powered by rotational energy. Energy accumulated in local fields is radiated into space by coronal flares. Therefore, it is most important to identify mechanism generating differential rotation of late type stars, which eventually continuously generates local magnetic fields and flares in which magnetic field energy is radiated into space. In fact it is a consistent transformation of mechanical energy into magnetic energy and eventually transformation into heat.

In our opinion in late type stars simultaneously exist two essentially independent types of magnetic field: strong dipolar SD and weak multipolar WM fields. One can assume, that in some cases generated local magnetic fields can shape without dissipation and eventually can create global magnetic fields ( $\alpha^2$  mechanism). The example: OT Ser which showed transition from WM to SD state. We believe, that the opposite scenario also is possible. In the latter case set of local fields compensates already existing global magnetic field and weaken it. Probably it can be seen in YZ CMi, where we noted decrease of the global magnetic field.

We expect, that the forthcoming influx of new observational data will verify the above considerations. On the other hand, existing classical models of flare eruptions must also be reviewed.

New flare models certainly should take into account quite strong global magnetic field penetrating hot coronal gas which surrounds the flare region. Modeling of coronal magnetic arches and loops describing local flares must include presence of the global field, which was found in some red dwarfs, see Donati et al. (2008) and Morin et al. (2008; 2010).

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